Extreme gravity – 1

DAWN III workshop

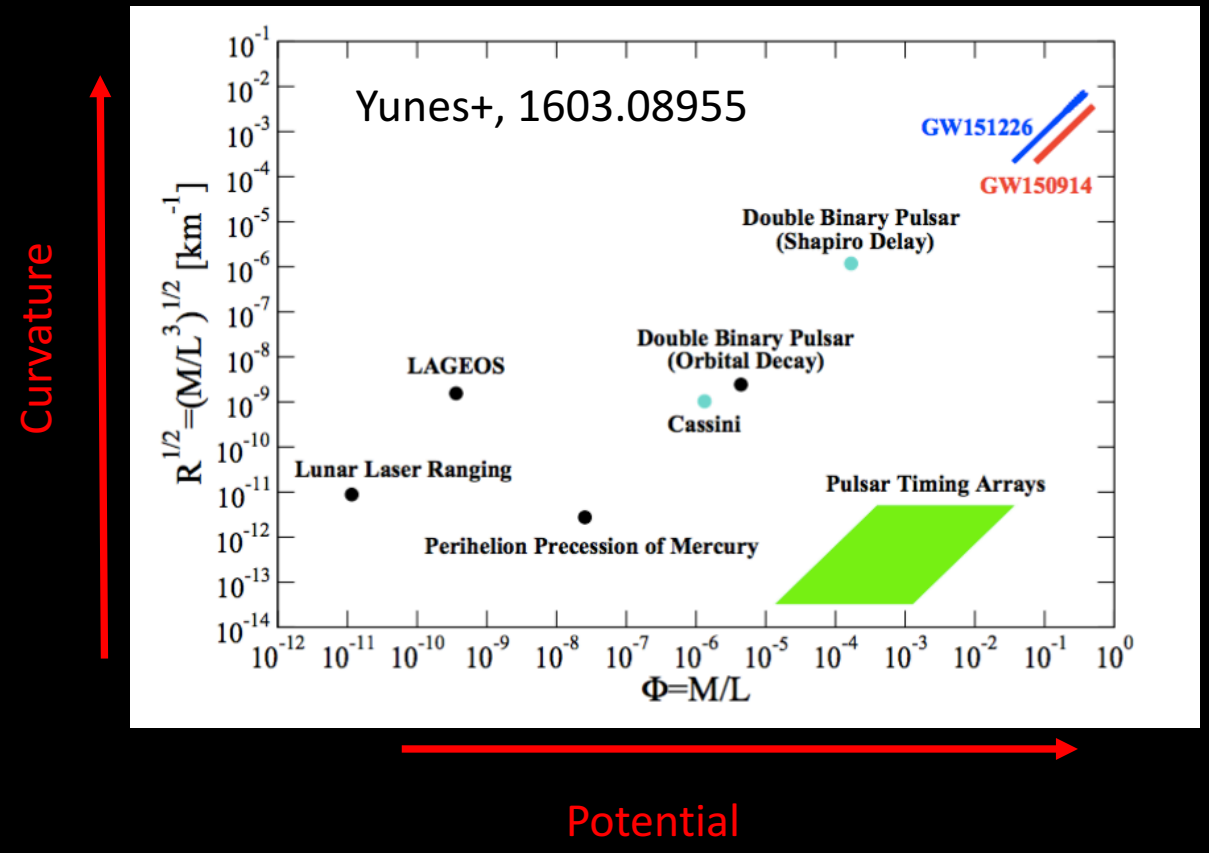
Syracuse July 6th 2017

Salvatore Vitale

MIT

What is it that we are trying to do

- General relativity has passed the first tests performed with gravitational waves
  - … beside all other tests
- In the future we can
  - Put better and better bounds
  - Find evidence for a deviation
  - Rank alternative theories?



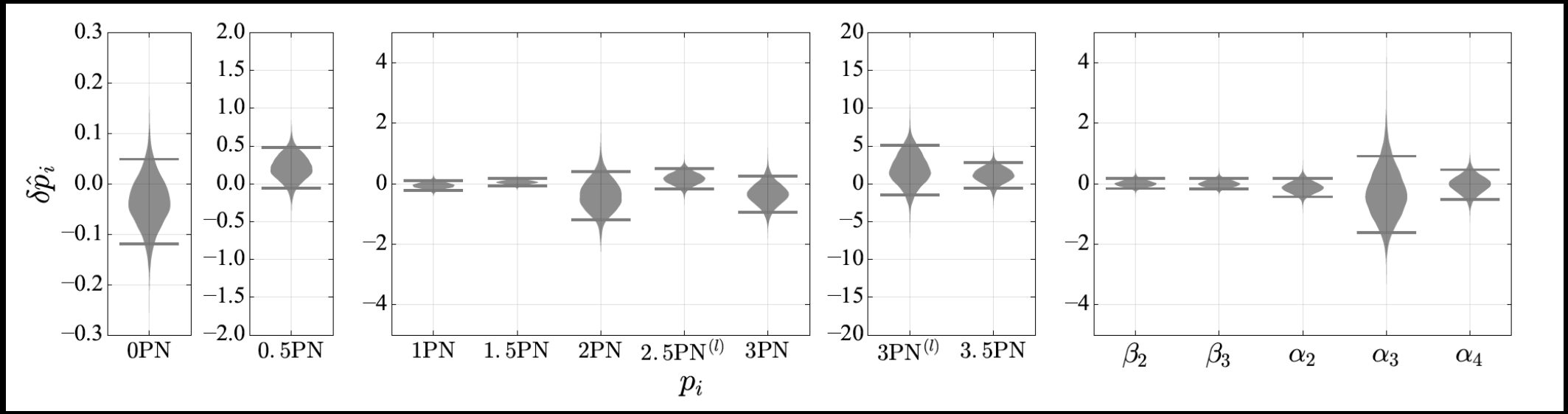
Current limits from LIGO

- LIGO has already set significant bounds during the first and second science run

- Followed a two-pronged approach
  - Consistency checks (i.e. is the data consistent with GR - and I don't care about what the real theory might be)
  - Test for specific theories

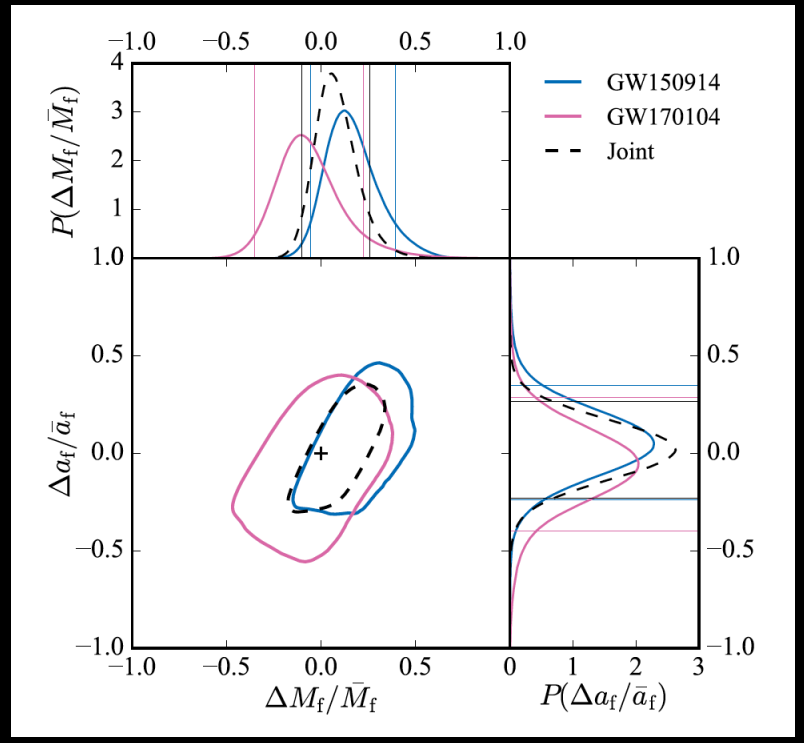
Consistency tests

- They answer questions such as:
  - Is the phase of the GW as one would expect within GR
  - Is the inference from the inspiral consistent with the merger and ringdown



Consistency tests

- They answer questions such as:
  - Is the phase of the GW as one would expect within GR
  - Is the inference from the inspiral consistent with the merger and ringdown



 LVC, PRL 118 221101

Consistency tests

- Advantages:
  - They do not require to have a model for the *true* theory of gravity
- Issues:
  - They do not immediately yield physical constraints

From generic to specific tests

- For many specific alternatives there is at least partial information on the expected waveforms

Theoretical Effect	Theoretical Mechanism	Theories	ppE b	Order	Mapping
Scalar Dipolar Radiation	Scalar Monopole Activation	EdGB [143, 145, 152, 153]	-7	-1PN	$\beta_{\rm EdGB}$ [143]
	BH Hair Growth	Scalar-Tensor Theories [60, 154]	-7	-1PN	$\beta_{\rm ST}$ [60, 154]
Anomalous Acceleration	Extra Dim. Mass Leakage	RS-II Braneworld [155, 156]	-13	-4PN	$\beta_{\rm ED}$ [144]
	Time-Variation of G	Phenomenological [140, 157]	-13	-4PN	$\beta_{\dot{G}}$ [140]
Scalar Quadrupolar Radiation Scalar Dipole Force Quadrupole Moment Deformation	Scalar Dipole Activation due to Grav. Parity Violation	dCS [143, 158]	-1	$+2$PN	$\beta_{\rm dCS}$ [149]
Scalar/Vector Dipolar Radiation	Vector Field Activation due to Lorentz Violation	EA [111, 112], Khronometric [113, 114]	-7	-1PN	$\beta^{(-1)}_{\text{Æ}}$, $\beta^{(-1)}_{\rm KG}$ [115]
Modified Quadrupolar Radiation			-5	0PN	$\beta^{(0)}_{\text{Æ}}$, $\beta^{(0)}_{\rm KG}$ [115]
Modified Dispersion Relation	GW Propagation	Massive Gravity [159–162]	-3	$+1$PN	$\beta_{\rm MDR}$ [148, 159]
		Double Special Relativity [163–166]	$+6$	$+5.5$PN	
		Extra Dim. [167], Horava-Lifshitz [168–170]	$+9$	$+7$PN	
		gravitational SME ($d=4$) [82]	$+3$	$+4$PN	
		gravitational SME ($d=5$) [82]	$+6$	$+5.5$PN	
		gravitational SME ($d=6$) [82]	$+9$	$+7$PN	
		Multifractional Spacetime [171–173]	3–6	4–5.5PN	

LIGO

Cosmic Black-Hole Hair Growth and Quasar OJ287

M.W. Horbatsch[1] and C.P. Burgess[1,2]

asymptotic spatial gradient in the scalar field. Most remarkably, the amount of scalar hair so induced is independent of the strength with which the scalar couples to matter. We argue that Jacobson's Miracle Hair-Growth Formula© implies, in particular, that an orbiting pair of black holes can radiate *dipole* radiation, provided only that the two black holes have different masses. Quasar OJ 287, situated at redshift $z \simeq 0.306$, has been argued to be a double black-

LIGO

Generation and propagation

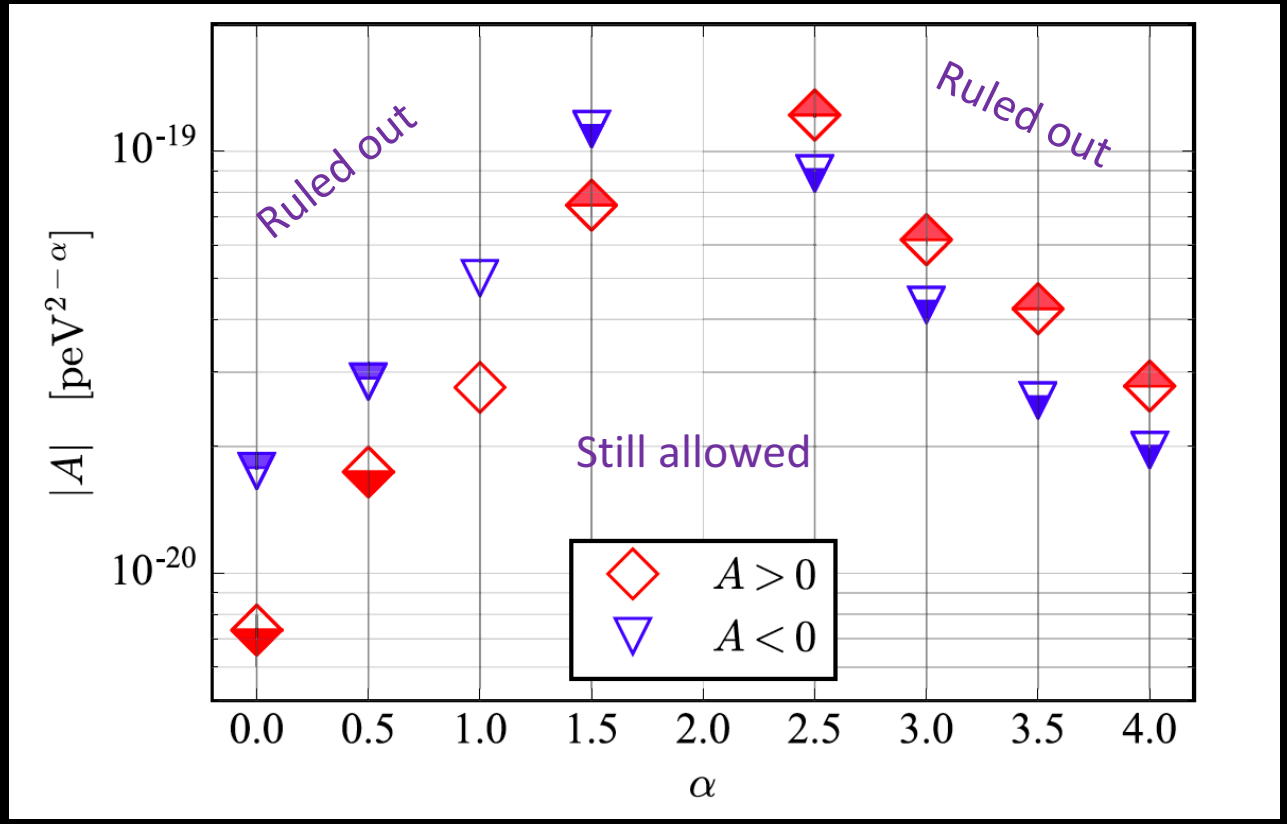
- Deviations from GR can affect the
  - Generation of gravitational waves (affect the Lagrangian)
  - Propagation of gravitational waves

- For the latter, magnitude of deviation increases with distance

Lorentz Invariance

- Starting with GW170104, the LVC has tested for modified dispersion relation (affects propagation)

$$E^2 = p^2c^2 + Ap^\alpha c^\alpha \quad \alpha > 0$$



LVC, PRL 118 221101

LIGO

Caveats

- For most (all?) the proposed alternatives to GR that affect generation:
  - Often only the leading orders are known
  - The non-GR terms are only known for the inspiral
  - No numerical simulations have ever been performed (or maybe 1, Manuela's talk)
- Estimates in the literature (Yunes+, others) use the inspiral phase only.

A PN-based approach

- In spite of all caveats, it is useful to consider the leading order effect of the proposed alternative theories
- Associate each theory with the equivalent leading post-Newtonian (PN) order

- The lower the PN, the lower the relevant frequencies
  - It makes evident which part of the bandwidth is more useful
  - Often comes with physical intuition

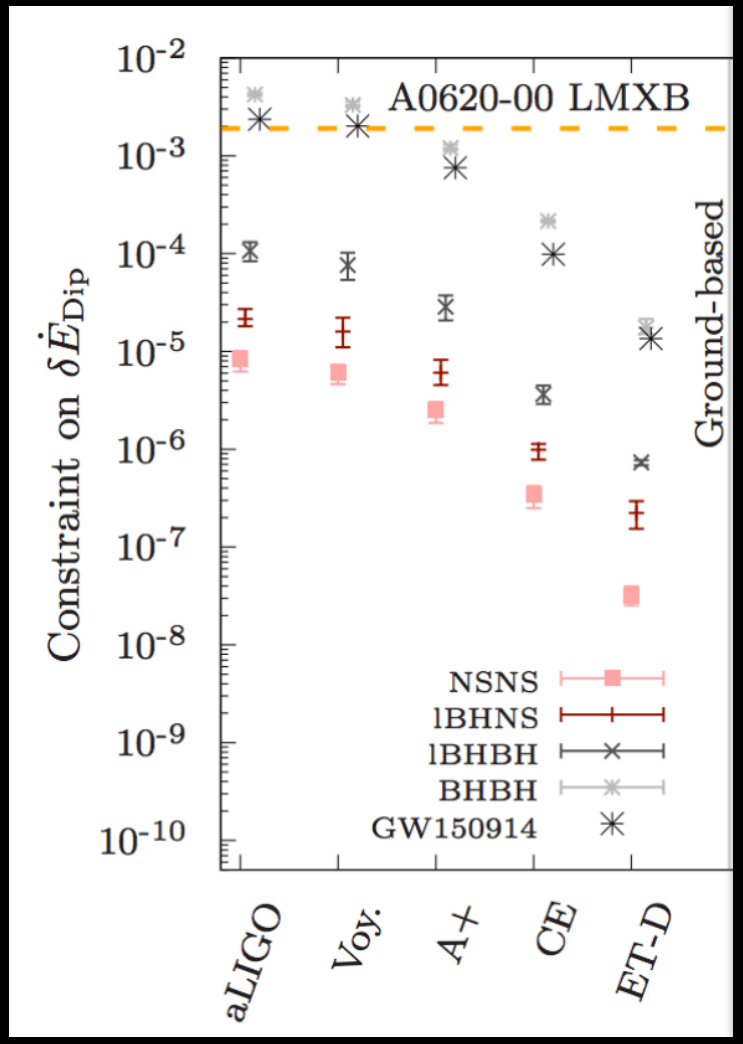
LIGO

Example: dipole radiation

- In GR: no dipole
- In some alternative theories: extra scalar or vector fields can activate dipole radiation
  - E.g. scalar-tensor theories (requires neutron stars)
- Net effect:
  - Some energy is lost to dipole radiation
  - System inspirals faster than it would in GR
  - More important at high separation/low velocity

$$\dot{E} = \dot{E}_{\mathrm{GR}} + \delta\dot{E}_{\mathrm{Dip}} v^{-2}$$

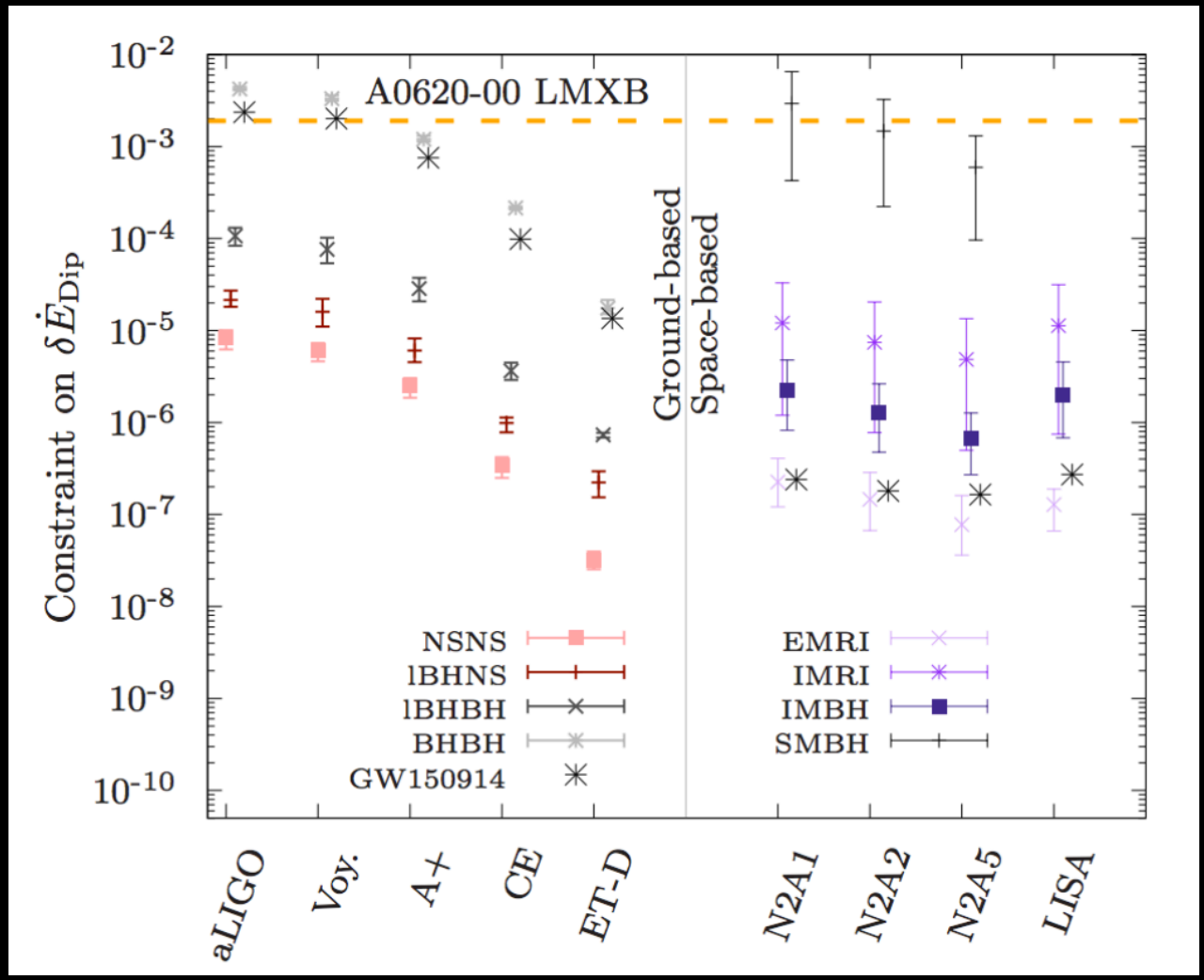
Example: dipole radiation



7/6/17 Chamberlain+, 1704.08268

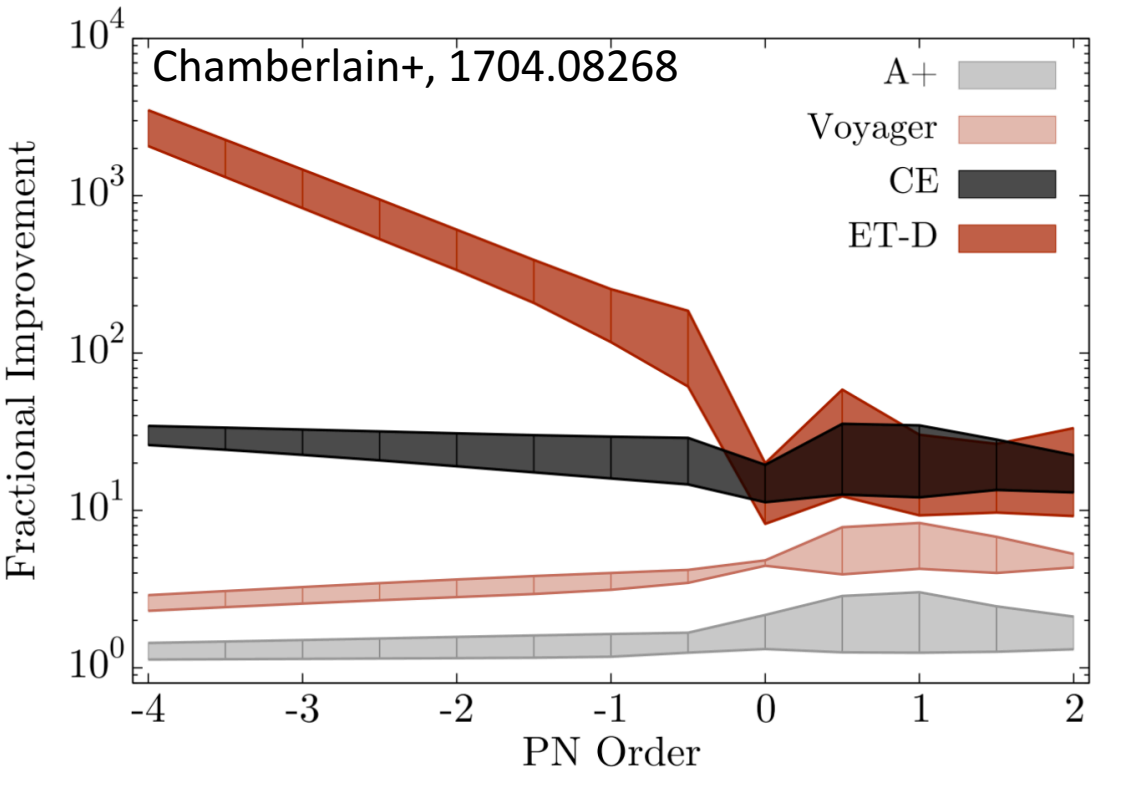
Example: dipole radiation

$$\beta = -\frac{3}{224}\delta\dot{E}_{\rm Dip}\eta^{2/5}$$



7/6/17 Chamberlain+, 1704.08268

The role of low frequency

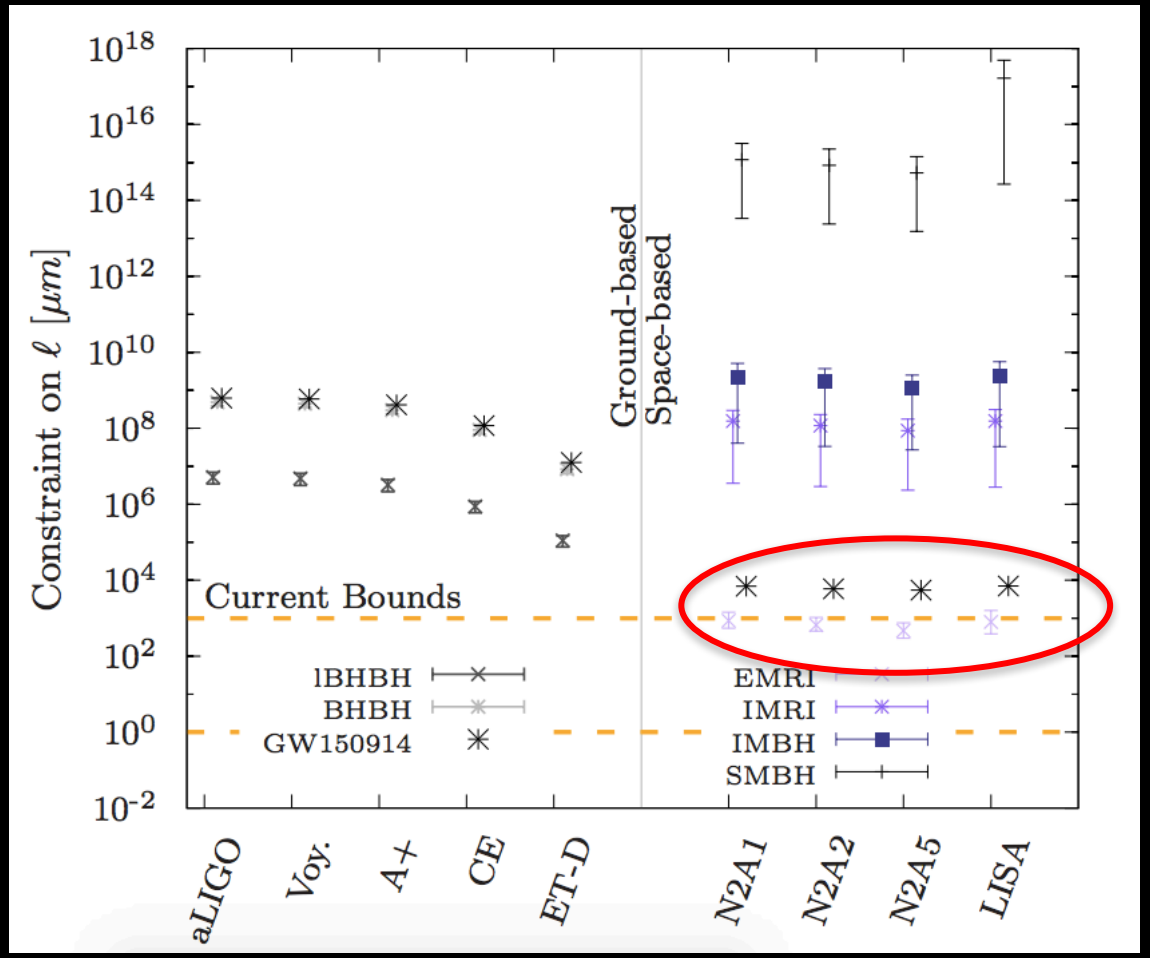


Showing improvement in bounds w.r.t. aLIGO design for GW150914-like events

- For theories that enter at very low PN order, ET would do better due to ~1Hz sensitivity
- ET ~100 times better than CE at -4PN
- ET ~5-10 times better at -1PN

What's at -4PN?

- Theories that enter at -4PN are
  - Extra large (~um) dimension
  - Time varying G
- For both theories, LISA can do much better (due to lower frequency)
- Uncertain rates
  - IMBH, IMRI: zero evidence
  - EMRI: few-O(1000)/yrs (Babak+ 1703.09722)



Chamberlain+, 1704.08268

LIGO

What's at -1PN?

- Dipole radiation
- Bounds from 3G instruments comparable with LISA
- Potentially, more sources than for LISA (can build cumulative posteriors)

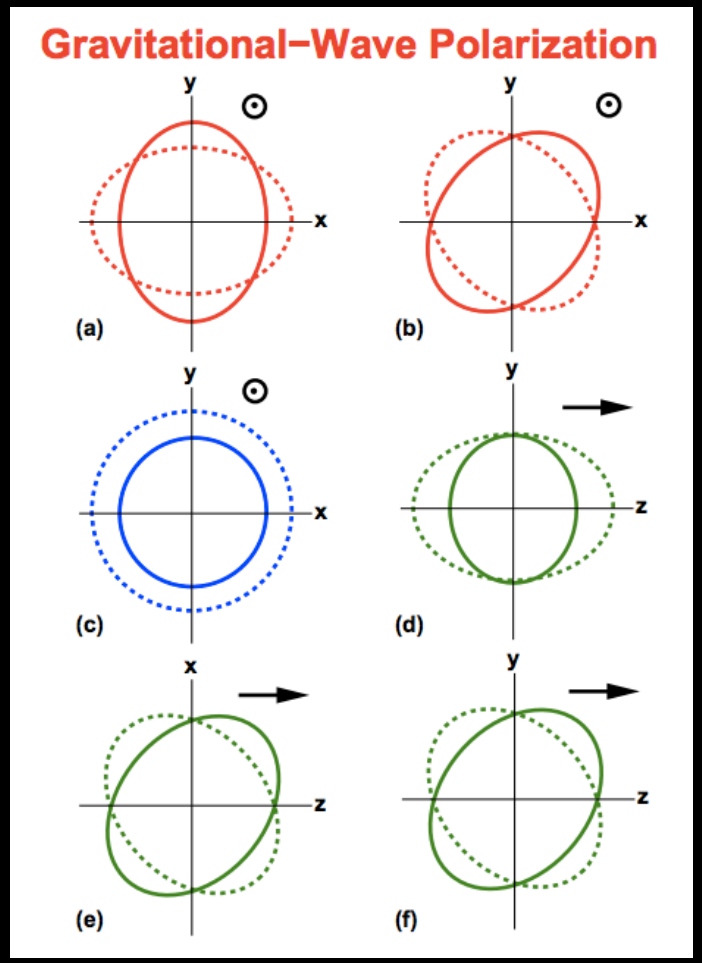
Positive PN

- All other alternative theories enter at 0 or positive PN order
- CE and ET yield comparable bounds
- CE typically will have larger SNR

Extra polarizations

- Metric theories of gravity allow for up to 6 polarizations
  - 3 transverse

- Need a network to probe for extra polarizations



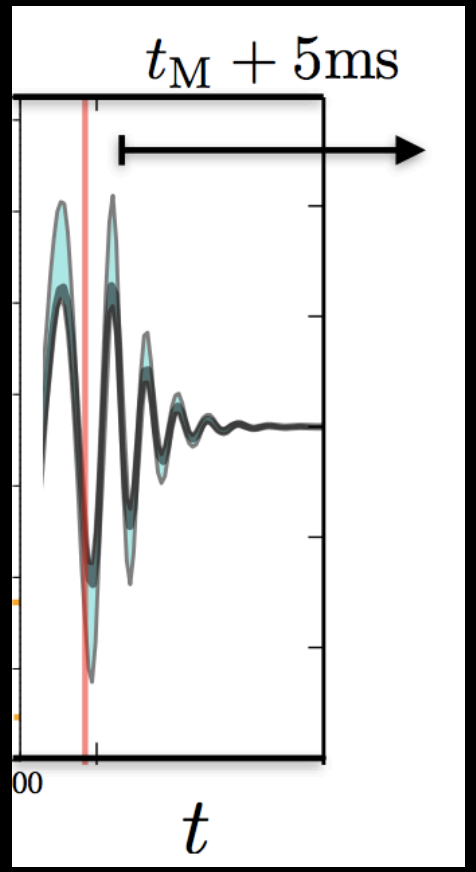
Will, 1403.7377

Are black holes black holes?

- Decoding the ringdown would
  - Help distinguish Kerr black holes from exotic objects (boson stars, gravstar…, Cardoso+ 1602.07309)
  - Help testing the no-hair theorem
  - Be really cool!!

- Extremely challenging with 2G, most likely need 3G
- *A lot* of ongoing work from the data analysis side

LVC, PRL 116, 221101



Realistically, what will be do?

- Very likely, we will setting up tighter and tighter bounds for the next years

- In the events of evidence that GR cannot explain the data
  - We can rank the *proposed* alternative theories and see which one matches the data best
  - We can estimate the characteristic parameters of that theory

What's missing?

- TODAY, in nearly all cases we do NOT have:
  - Modification of merger and ringdown
  - Effect on spin precession
  - Numerical simulations

Theory

NR

- (Even within GR):
  - Eccentricity
  - Better understanding of neutron star equation of state

- We will most likely need all of these when statistical uncertainties go down